

Imperfect World of $\beta\beta$ -decay Nuclear Data Sets?

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(Dated: March 12, 2015)

The precision of double-beta ($\beta\beta$) decay experimental half-lives and their uncertainties is reevaluated. A complementary analysis of the decay uncertainties indicates deficiencies due to small size of statistical samples, and incomplete collection of experimental information. Further experimental and theoretical efforts would lead toward more precise values of $\beta\beta$ -decay half-lives and nuclear matrix elements.

PACS numbers: 23.40.-s, 21.10.-k, 28.20.Ka, 29.87.+g

Double-beta decay was proposed by M. Goeppert-Mayer [1] as a nuclear disintegration with simultaneous emission of two electrons and two neutrinos

$$(Z, A) \rightarrow (Z + 2, A) + 2e^- + 2\bar{\nu}_e. \quad (1)$$

There are several double-beta decay processes: $2\beta^-$, $2\beta^+$, $\epsilon\beta^+$, 2ϵ and possible decay modes: two-neutrino (2ν), neutrinoless (0ν) and Majoron emission (χ^0)

$$(Z, A) \rightarrow (Z \pm 2, A) + (2e^\pm) + (2\bar{\nu}_e, 2\nu_e \text{ or } \chi^0). \quad (2)$$

The $\beta\beta$ -process has been extensively investigated in the last 80 years [2, 3]. These efforts have led to observations of the two-neutrino decay mode and deduction of decay half-lives. It is the rarest presently-observed nuclear decay. In a recent analysis of $\beta\beta$ -decay data, A.S. Barabash [4] claimed that we could deduce precise values of experimental half-lives and extract the corresponding nuclear matrix elements (NME). Unfortunately, these claims are premature and not very beneficial for the field. The main goal of this work is to investigate the present status of $\beta\beta$ -decay research, reanalyze the data, and produce realistic assessments and recommendations that could accelerate overall progress.

The $\beta\beta$ -decay $T_{1/2}^{2\nu}$ are available from multiple sources [4, 5]. A brief summary of the recent National Nuclear Data Center (NNDC) evaluated or adopted values is shown in Table I and plotted in the lower part of Fig. 1. This plot contains 12 adopted half-lives for nuclei of practical interest. The NNDC evaluation is completely based on standard U.S. Nuclear Data Program procedures, and its validity has been extensively scrutinized using theoretical predictions and nuclear systematics arguments [5].

To gain a complementary insight on the statistical sample size, as shown in the Table I, I will resort to a non-traditional approach and consider Benford's Law [6]. Figure 1 illustrates that relatively large statistical samples for thermal neutron capture cross sections and B(E2) \uparrow adopted values of 421 and 427 nuclei [7, 8], respectively, are in agreement with the law. The Pearson's cumulative test statistic values for nuclear reaction and structure data sets are 8.584 and 15.0, respectively.

TABLE I: Adopted $\beta\beta$ -decay $T_{1/2}^{2\nu}$ for $0^+ \rightarrow 0^+$ transitions. Data are taken from the Ref. [5].

Parent nuclide	$T_{1/2}^{2\nu}(\text{y})$	$T_{1/2}^{2\nu+0\nu+\chi^0}(\text{y})$
⁴⁸ Ca	$(4.39 \pm 0.58) \times 10^{19}$	$(3.49 \pm 1.99) \times 10^{24}$
⁷⁶ Ge	$(1.43 \pm 0.53) \times 10^{21}$	
⁸² Se	$(9.19 \pm 0.76) \times 10^{19}$	
⁹⁶ Zr	$(2.16 \pm 0.26) \times 10^{19}$	
¹⁰⁰ Mo	$(6.98 \pm 0.44) \times 10^{18}$	
¹¹⁶ Cd	$(2.89 \pm 0.25) \times 10^{19}$	$(1.40 \pm 0.80) \times 10^{21}$
¹²⁸ Te	$(7.14 \pm 1.04) \times 10^{20}$	
¹³⁰ Te	$(2.34 \pm 0.13) \times 10^{21}$	
¹³⁰ Ba	$(8.37 \pm 0.45) \times 10^{18}$	
¹⁵⁰ Nd	$(2.00 \pm 0.60) \times 10^{21}$	
²³⁸ U		

These cumulative values could be compared with upper-tail critical values of χ^2 distribution [9] with 8 degrees of freedom. A similar analysis for the adopted values of $\beta\beta$ -decay $T_{1/2}^{2\nu}$ [5] is not possible because one is supposed to have at least 5 counts in each of the nine bins [10], or the number of $\beta\beta$ -decay observations has to quadruple. Consequently, there is no sense in applying it to the presently-available $\beta\beta$ -decay half-lives due to the limited number of observed transitions and large experimental uncertainties.

From the dawn of the $\beta\beta$ -decay era researchers knew the importance of complete experiments when both released energy and angular distribution of decay products have been recorded. The first direct observation of two-neutrino decay mode in ⁸²Se [11] and subsequent observations in ¹⁵⁰Nd and ⁴⁸Ca [12, 13] were made using such techniques. These discoveries employed the time projection chambers (TPC) that contained small amounts of target material and, consequently, generated limited statistics. The experiments were very complex; however, observation of two-electron events has provided clear evidence of the double-beta decay process.

Further developments have progressed using advanced commercially-available detectors [14, 15] and large quantities of enriched isotopes. Unfortunately, the usage of commercial detectors often leads to incomplete exper-

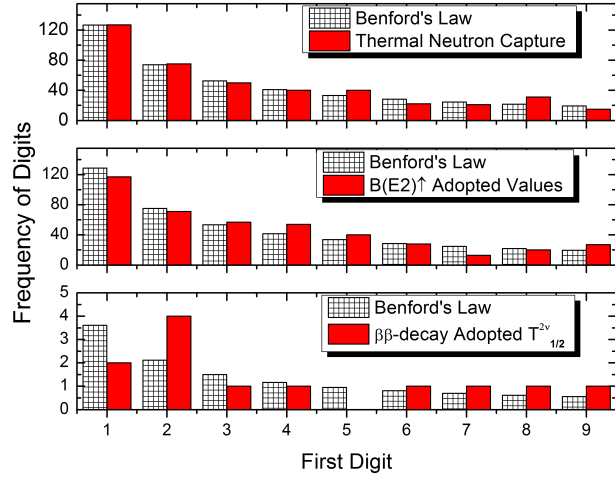


FIG. 1: Benford's distributions for adopted values of thermal neutron capture cross sections, $B(E2)^\dagger$ and $\beta\beta$ -decay $T_{1/2}^{2\nu}$ data sets [5, 7, 8].

iments when only energy release information has been collected. To illustrate this point, we should consider $\beta\beta$ -decay search in ^{76}Ge . The lower part of Fig. 2 depicts a chronological record of the measurements [14]. The different half-life values with large uncertainties for two-neutrino mode of decay are often explained by the relatively high background in the earlier experiments. These experiments were based on an essentially-single source of enriched ^{76}Ge isotope and slightly different detector fabrication and shielding technologies. All of these measurements relied heavily on an excellent energy resolution of Ge detectors and suffered from the lack of electron tracking information. Consequently, a final $\beta\beta$ -decay spectrum could contain the contribution of single-electron events. High energy resolution is absolutely essential for observations of neutrinoless $\beta\beta$ -decay, when decay will produce a sharp peak corresponding to a Q-value between parent and daughter nuclei. Unfortunately, the quantum world is very diverse, and background processes may affect the results. It has been demonstrated recently that γ -ray transitions in Pb and ^{76}Ge could produce a 2039 keV signal and obscure the decay signature [18, 19].

Electron tracking information is crucial in $\beta\beta$ -decay research. An observation of two-electron events in addition to energy release information would help to suppress the radioactive background and decisively prove $\beta\beta$ -decay process in a particular nucleus. Perhaps, in addition to HPGe technologies, it could be interesting to remeasure ^{76}Ge $T_{1/2}^{2\nu}$ in a NEMO experiment that is based on a more extensive set of observables [20], or explore germanium tetrafluoride (GeF_4). Similar scenarios have been developing with $\beta\beta$ -decay search in ^{136}Xe [21–23].

In light of this disclosure, it becomes clear that excel-

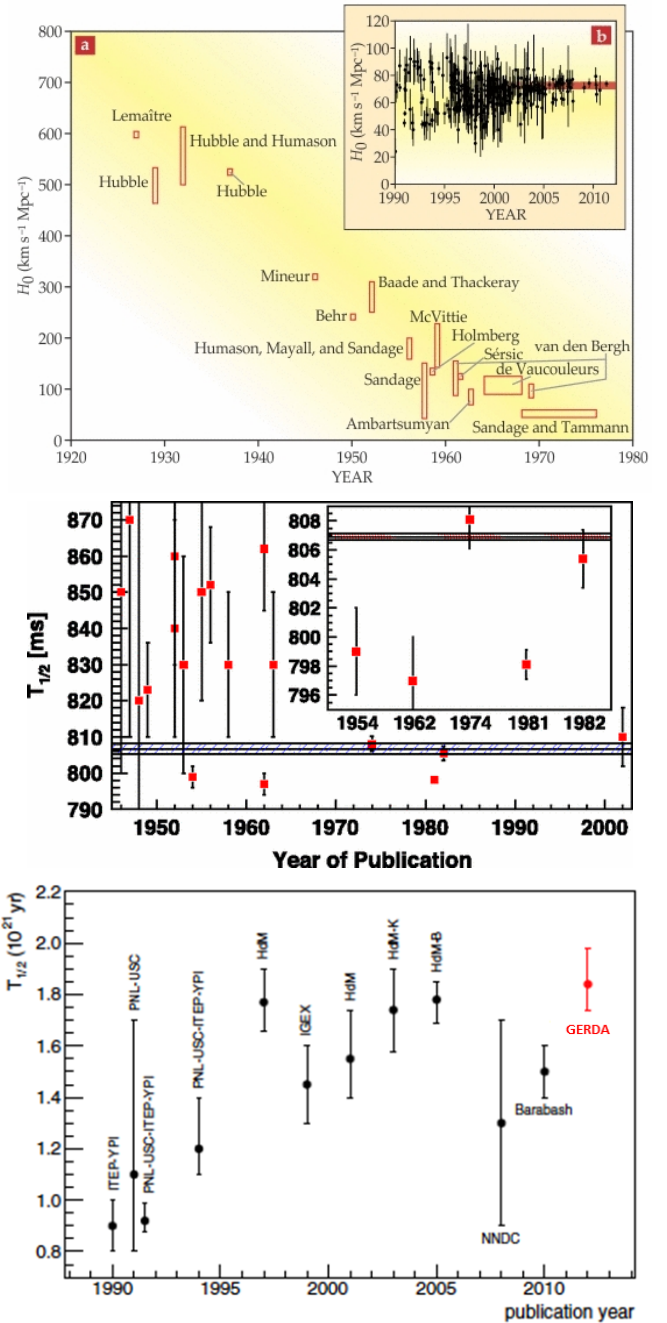


FIG. 2: Chronological record of three different groups of measurements: Hubble constant [16], $T_{1/2}$ of $^6\text{He}(\beta)$ [17] and $^{76}\text{Ge}^{2\nu}(\beta\beta)$ [14]. These graphs are courtesy of the cited publications.

lent energy resolution of HPGe detectors alone may not be sufficient for an observation of neutrinoless mode in ^{76}Ge . Therefore, the preset day state-of-the-art GERDA and Majorana experiments [14, 15] may not be able to provide an ultimate answer due to the incomplete nature of the data recording.

Analysis of the lower part of Fig. 2 shows that the “precise” $T_{1/2}^{2\nu}$ value of Barabash [4] strongly contradicts the latest result of the GERDA experiment [14]. This example shows that it is too early, at this point, to state a high precision of adopted half-lives and NME, and large error bars of the previous NNDC evaluation [24] are more appropriate. All NNDC values were produced from the experimental half-lives when new measurements would trigger the data reevaluation every 5-7 years.

A complementary analysis of the upper and lower parts of Fig. 2 shows that the presently-discussed situation with $\beta\beta$ -decay measurements is not unique in physics. It is rather a common occurrence when initial, pioneering measurements are not very accurate and often discrepant. It definitely has happened to Hubble constant and ${}^6\text{He}$ β -decay experiments [16, 17], as shown in the upper and middle part of Fig. 2. This figure content is based on original graphs borrowed from the Refs. [14, 16, 17]. Other recent cases of inconsistent data include the discrepant decay scheme and half-life of ${}^{139}\text{Ba}$ [25], and cross section values. In the recent review of neutron cross section deficiencies, M.B. Chadwick [26] compiles an impressive list that includes ${}^{235}\text{U}$ and ${}^{197}\text{Au}$ fast neutron capture cross sections. The last cross section value was used in calibration of the stellar nucleosynthesis KaDO-NiS database [27] and has a broad impact across neutron physics. We are surrounded by a large number of imperfect nuclear data sets and constantly work on their improvement.

The experimental $\beta\beta(2\nu)$ -decay half-lives include contributions from the nuclear structure effects and decay kinematics. $T_{1/2}^{2\nu}$ values are often described as follows

$$\frac{1}{T_{1/2}^{2\nu}(0^+ \rightarrow 0^+)} = G^{2\nu}(E, Z) |M_{GT}^{2\nu} - \frac{g_V^2}{g_A^2} M_F^{2\nu}|^2, \quad (3)$$

where the function $G^{2\nu}(E, Z)$ results from lepton phase space integration and contains all the relevant constants [2]. Equation (3) highlights a direct dependency of experimental NME on the calculated values of phase space factors.

Both Barabash’s and NNDC’s evaluated NME were based on the best available phase space factor calculations in 2010 and 2013, respectively [2, 29, 30]. Table II shows the evolving values of ${}^{76}\text{Ge}$ phase space factors, and the table data raise a question about calculation limitations and possible model dependency of the PSFs. The observed discrepancies between recent calculations of Kotila & Iachello [30] and Stoica & Mirea [31] create reason for concern. The exact values of phase space factors are needed in order to deduce the precise values of experimental NME for comparison with recent theoretical calculations of Senkov and Horoi [32]. It will be highly beneficial for the field if a third group of theorists will clarify the situation. The formula (3) gets even more complex for the neutrinoless mode where half-life

TABLE II: ${}^{76}\text{Ge}$ $\beta\beta$ -decay phase space factor (PSF) values in 10^{-21} yr^{-1} for $0^+ \rightarrow 0^+$ transition.

Authors	Year	PSF
Boem & Vogel [2]	1987	130.54
Doi <i>et al.</i> [28]	1993	53.8
Suhonen & Civitarese [29]	1998	52.6
Kotila & Iachello [30]	2012	48.17
Stoica & Mirea [31]	2013	43.9

also depends on a neutrino mass, and neither neutrino mass or NME can be easily disentangled.

Finally, the double-beta decay experimental half-lives have been reanalyzed using standard nuclear data techniques. The analysis of the two-neutrino mode of $\beta\beta$ -decay data sets indicates their uncertainties are high due to relatively small experimental statistics and incomplete collection of decay information. We live in an era of $\beta\beta$ -decay observations with large uncertainties. It may take years before future complete or “almost” complete experiments like low-pressure TPC [11–13] or simultaneous measurement of positrons and γ -rays [33] will improve the data. The precision of experimental NME strongly depends on the quality of phase space factors, and additional theoretical calculations are necessary to clarify the discrepant results.

Double-beta has been an exciting nuclear physics phenomenon that has slowly revealed its experimental signatures in the last 30 years. It may take many painstaking experimental and theoretical efforts before the process will be well understood and measured. It is not an unusual situation in a history of science; in fact, it is a very common case. Therefore, one can assume that it may take another 30 years before all decay modes, experimental half-lives and NME values will be finalized.

The author is indebted to Dr. M. Herman (BNL) for support of this project and grateful to Dr. V. Unferth (Viterbo University) for help with the manuscript. This work was funded by the Office of Nuclear Physics, Office of Science of the U.S. Department of Energy, under Contract No. DE-AC02-98CH10886 with Brookhaven Science Associates, LC.

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